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# Towards a Danish Power System with 50% Wind - Smart Grids Activities in Denmark

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*Abstract*— **The new Danish Energy Strategy implies 50% wind power penetration for the Danish electric power system by 2025. Accordingly, it is the vision to develop the Danish electric power system into world's best renewable based electricity system, and many research and development activities have taken place with collaborations nationally and internationally. This paper describes the research activities in relation to implementation of renewable energy targets set out by the Danish Energy Strategy and initiatives of the EcoGrid.dk program to facilitate this process. Based on the analysis and evaluation of research needs and related research activities, the remaining gaps are identified for future activities to support a transition into sustainable energy networks.**

***Index Terms*—SmartGrids, wind power, distributed generation, smart demand, MicroGrids, Virtual Power Plant, electric power systems**

## I. Introduction

THE new energy strategy by the Danish government-"A visionary Danish energy policy", published on 19 January 2007, outlined the energy development policy towards year 2025 [1]. The goal is to increase the share of renewable energy to at least 30% of the total energy consumption by 2025. This is expected to require wind power generation in 2025 equal to 50% of the national electricity consumption, which will lead to tremendous changes for the Danish electric power system in the future [1].

In the past, the Danish electric power system relied primarily on the centralized fossil-fuel based power plants, serving the passive demands, with power exchanges via a limited number of interconnections linking with neighboring countries. Control and operation of the traditional power system used to be successful and less complicated, though such a system is environmentally polluting, and unable to fulfill the increased needs from the market and customer.

Driven by the mainly environmental issues, especially climate change, rapid development of wind power and other renewable energies have been taking place worldwide. As a leading wind power country, Denmark has achieved a record of 20% penetration of wind power (2007 data), and is now moving towards the new target set out by the new national strategy [2]. With the valuable experiences accumulated so far, it has been anticipated that the technical challenges for 2025 scenario of 50% wind penetration mainly exist in power system balancing, market services and operational security and economy. Accordingly, many research and development activities have been established in Denmark, with national-wide and international collaborations. These research activities are well in line with the new energy strategy as well as the European Union SmartGrids vision for future electricity network [16].

Among these activities, the EcoGrid.dk is the principal research program on the national level, led by the Danish TSO (Transmission System Operator) Energinet.dk, together with joined forces of a broad spectrum of stakeholders including power companies, manufacturers, consultants and research institutes both in and out of Denmark, to develop a roadmap for transforming Danish power system into the world best renewable based electricity network [3-7]. The overall objective of EcoGrid.dk is to develop new long term technologies and market solutions for power grid and systems, with reference to the Danish power system. The focus is the identification, evaluation and implementation of new architectures, concepts, structures and developments of new solutions for enhanced and optimized integration of renewable energy sources, expansion of transmission and distribution networks, active customer participation, advances in information and communication technologies, markets and pioneering concepts of system control and operation in the Danish power system [3]. The outcome of the EcoGrid.dk program is expected to provide a valuable reference and guidance in future research project formulations for several public research funding programs. The EcoGrid.dk is divided into three main phases over a project period of approximately 3 years as follows:

- Phase 1 (mid 2007-2009): General description and analyses of demand and development of the Danish power system with increased volumes of renewable energy (RE).
- Phase 2 (2009-2010): Specific projects, analyses and recommendations to Energinet.dk with the main focus on research activities to develop and embed new technologies with advanced market solutions.
- Phase 3 (2010-2011): Technologies are implemented in real environment and demonstrated with subsequent

The work in this paper is based on a larger research program EcoGrid.dk sponsored by Energinet.dk, the Danish Transmission System Operator.

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adoption and implementation in Energinet.dk and the Danish power system.

The objective of this paper is to identify and synthesize the challenges facing future power systems with high penetration of wind, and describe and summarize the research activities aiming at delivering 50% wind integration into the Danish power system, based on mainly the outputs from the EcoGrid.dk Phase I, as well as others. The rest of the paper is organized as follows; Section II overviews of the electric power system in Denmark and challenges encountered due to increased wind and other renewable energy supply participants in recent years. Section III analyses the requirement for future power systems with 50% wind penetration and describes various relevant research activities. Section IV concludes the paper with the outline of future scope of work.

## II. Overview of Danish Electric Power System

### A. General facts

Denmark is situated geographically in the northern part of Europe, and electrically between the two large power systems, which are primarily based on thermal and hydro power respectively (see Fig 1), i.e. the UCTE (mainland European system including Western Denmark) and Nordel power systems (Eastern Denmark, Sweden, Norway and Finland) [8-11]. As such, the Danish power system has the uniqueness that, as one country, Denmark has two electric systems of Eastern and Western DK, connected to the two synchronized large power systems respectively, while both of them are actually dispatched by the same market system - the Nordpool electricity market [12]. Energinet.dk is the national transmission system operator (TSO) owning and operating the power networks at 400 kV, 220 kV 150 kV, and 132 kV. Meanwhile, several AC and HVDCs are linking Denmark with neighboring countries like Germany, Sweden and Norway [10]. Another HVDC link between Denmark and Netherlands is now under discussion. There is no electric connection between Eastern and Western DK, but a submarine HVDC link is under construction.

The total installation capacity of power generators by the end of 2005 is about 13 GW, while the total electricity consumption is 36 TWh. The growth in electricity consumption has been relatively slow. From year 1995-2005, the total electricity consumption has been increased by 7% [2]. The major generation technologies include large and small size combined heat-electricity plants (CHPs), wind turbines, biomass plants and etc, without hydropower. In recent years, the share of wind power has been largely increased, and in 2007 the wind power generation corresponded to 20% of the electricity consumption. The wind penetration is higher in some local grids and bidirectional flows exists.

### B. Challenges encountered

The challenges encountered in operating and developing the Danish power system can be summarized from the perspectives of environment, security of supply, economy, and flexibility. The primary challenge comes from the public concerns of climate change and energy crisis. Accordingly over the past decades, Danish power system has incorporated more wind turbines and other distributed generation units (DGs). Since 1980s, the system has evolved significantly from relying on centralized fossil fuel based thermal generations to DGs based situation as seen in Fig. 2. This has benefited the nation by reduced primary energy consumption and carbon emission [2], though some side impacts have been introduced to its power system. It is foreseen that the amount of wind power installation will be doubled from the current 3 GW to about 6 GW according to the new energy strategy, and the amount of traditional CHP generation is intended to be reduced at the same time. Due to political and legislation reasons, the trend in Denmark is to build more wind farms located offshore, where wind resources are more steady and abundant.

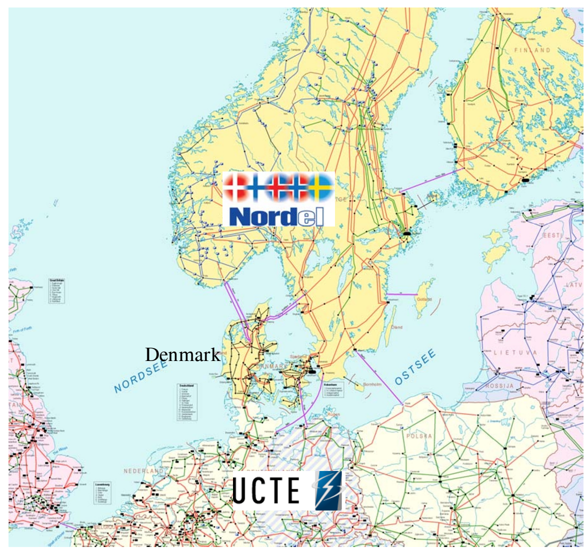
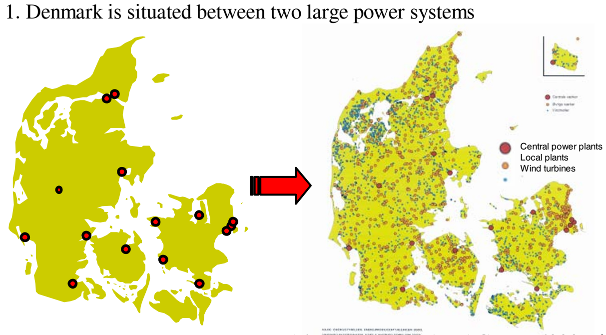



Fig. 1. Denmark is situated between two large power systems




16 central power plants

16 central+1000 local CHPs+6000 wind turbines

Fig. 2. Evolution of Danish power systems from the centralized (left) to distributed (right) system during 1980-2005

The current level of about 20% wind penetration is considered moderate, but the security of supply and operational cost for running such a system have become rising issues attracting more and more attention. These issues are mainly attributed to wind power's special features of very limited predictability and reliability that has caused significant difficulties in daily management of system balance. As an example, during the hurricane of January 2005 that struck the Western Denmark, in which the forecasted wind production deviated from the actual production by up to 1800 MW, due to high wind speeds (>20-25 m/s) and most wind turbines had to be shut down accordingly. During this event, the system security has been largely threatened as the reserve power was very close to exhaustion. Another example concerning system security happened in the local grid of the Bornholm island, which is located in the Baltic sea and considered as a representative distribution grid with already very high wind penetration of more than 32% in 2007 [14,15]. When the distribution grid is electrically isolated from the main grid of the Nordel system, the frequency stability can become problematic and most wind turbines have to be shut down, even during well planned such operations [14].

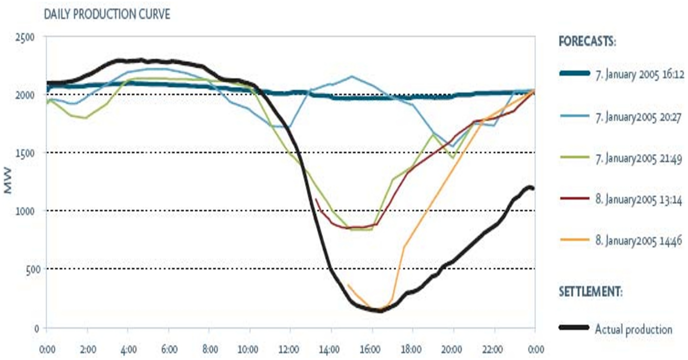



Fig. 3. The wind forecast and actual production during the January 8th 2005 hurricane in Denmark [13]

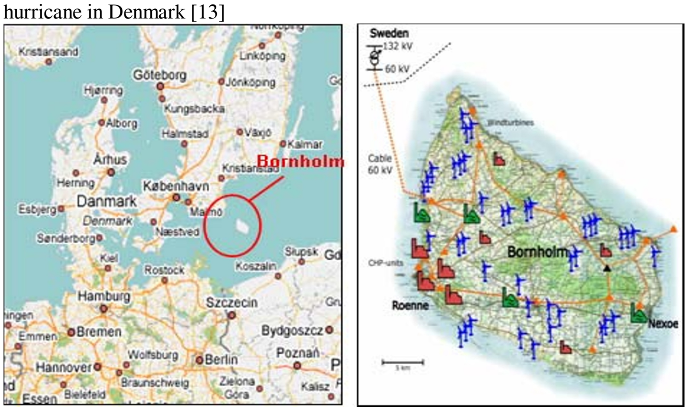



Fig. 4 The Bornholm power system as a representative of future Danish distribution system with high share of distributed and renewable energy, 1% area, population, and electricity consumption of whole Denmark, 27,000 customers, 30 MW wind capacity, and 63 MW peak load [15].

While the system security is endangered by increased wind power, the cost of operating such a system has been increased as well. According to Energinet.dk, the total cost of ancillary services in 2008 would exceed 1 billion DKK which is a substantial economic burden for the system operator and customers. Meanwhile, the market liberalization has also led to the increased interest from the customer side to participate into the electricity business.

The challenges encountered by the Danish power system provide valuable experiences for other countries in integrating wind power and other renewable energies into their power systems. The lessons learnt are also essential references in developing the roadmap for future electricity networks.

## III. Vision and Research Activities Towards Future Power Grid with 50% Wind Penetration

### A. *EcoGrid.dk Vision for the Future Grid*

Under the new national energy strategy, the Danish electric power system has the vision to become the world best renewable based electricity network to integrate 50% wind penetration by 2025. In the light of the challenges that have already been encountered, as well as technological advancements in the areas like information and communication technology (ICT) etc, the future Danish power grid must have the following as the key design objectives,

- *Sustainable to reduce carbon emission*
- *Secure to provide reliable electricity supply*
- *Economic to reduce prices and costs for other services*
- *Flexible to promote customer participation*

These objectives are well aligned with the European Union SmartGrids vision [16], and to realize them, the Ecogrid.dk Phase I has identified, evaluated and suggested new network architectures, concepts, structures and the developments of new solutions for enhanced and optimized integration of renewable energy sources, expansion of transmission and distribution networks, active customer participation, information and communication technologies, markets and pioneering concepts of system control and operation in the Danish power system. Many of the research needs have been defined based on past operational experiences and ongoing research activities in Denmark that are of high relevance.

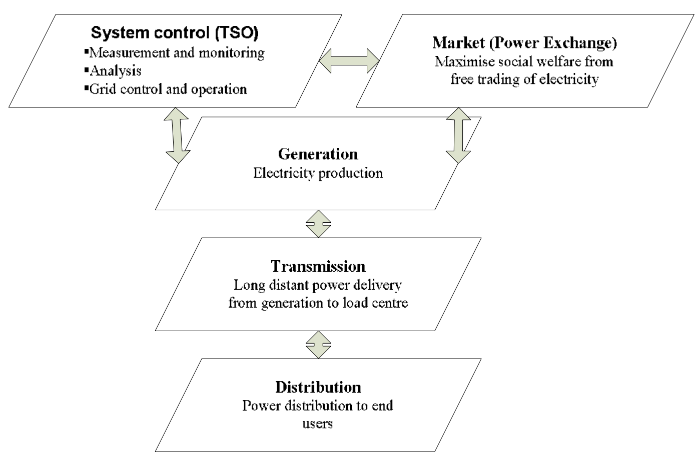



Fig. 5. Physical and functional overview of EcoGird.dk focused areas

The focused areas in EcoGrid.dk, as well as the related research projects, cover nearly all aspects of a power system and can be divided, from the physical structure and functional (organizational) perspective, into dimensions of market, system control, generation, transmission and distribution as shown in Fig 5. In the following sections, the current status and future requirements and research needs for the power system are reviewed, analyzed, and identified according to each dimension in the context of the Danish power system.

*B. The Electricity Market*

The market oriented development is driven primarily by the economy and flexibility points of view. Currently, the bulk electricity is traded within the Nordic system via a market system consisting of a day ahead market plus an hourly balancing market. Due to the very limited predictability and high intermittence, both the frequency and magnitude of power mismatch have increased largely under the current market system, resulting in high costs for ancillary services [7]. On the other hand, it is also needed to reform the market structure to allow active customer participation from both generation and demand sides especially concerning the end users and small size DGs, based on local and dynamic electricity price signals. Accordingly, the concept of Virtual Power Plant (VPP) is identified as one key solution to effectively aggregating the DGs, and even end users, for market participation. The VPP concept will be discussed later on in Section F. The flexibility of the future market should also enable easy coupling with international markets around Denmark through existing and planned interconnections.

Based on the analyses, the real time market framework to reduce the impact from forecasting uncertainty has been proposed in the EcoGrid.dk Phase I, and a research project on this topic has been established at Centre for Electric Technology (CET), Technical University of Denmark (DTU) [7]. The new market is expected to not only reduce the rising economic burden from buying ancillary services, but also contribute to improved system security by reducing the needs of system services. Other related research ideas in relation to the market issues include e.g. dynamical nodal pricing and ancillary service market to stimulate participations from all players and further bring down the cost.

*C. Power System Control*

The role of TSO is to operate and control the system by conducting tasks of Measurement and Monitoring, Analysis, and Grid Control and Operation. The research needs concerning the system control are mainly due to the need for enhancement of system security. As presented in Section II, it should be highlighted that the power balancing and new forecasting tool are the major concerns for future system control with considerable amount of wind power.

Today, the power system control function is far from fulfilling the future needs to deal with even higher penetration of wind and other renewables. The measurement and monitoring capability of the TSO is fairly limited due to the dependence on the slow, unsynchronized, and unreliable SCADA system, with poor and insufficient visualization, based on miscellaneous communication standards. The key tool for monitoring the grid status i.e. the alarming system can only list out all triggered warnings in the case of system events, however, without prioritized processing, root cause analysis, consequence evaluation, and even counter-reaction planning that leads to little support to on-line decision making in operating and controlling the power system [28].

The analyses that TSO can perform at present is primarily based on offline contingency analysis using offline system models through the deterministic approach, considering no worse than *N-1* situation. More importantly, the methods and tools are well established for load forecasting, however not for forecasting the wind power and other renewables of high fluctuating nature.

The present grid operation and control relies on traditional resources for frequency and power balancing, which is close to exhaustion from practical experiences and with little coordination between TSOs. In addition, the settings of the protection system concerning e.g. the operational limits are always fixed. Furthermore, the current distribution network is passive and invisible to the TSO, leading to less coordinated and coherent system wide control.

It is anticipated that future system control will incorporate revolutionary changes to better address the security issue by exploiting advancements in measurement and ICT technologies, as well as new measures for power balancing including storage techniques, and demand side options by e.g. smart demand technologies and integration with other energy sectors e.g. the district heating and transportation [6,17, 18]. Table I compares the current status and the projected future scenario concerning the power system control. The EcoGrid.dk has identified that the research and development efforts with respect to power system control should give priorities to new measures for power balancing, wind power forecasting, and PMU based Wide Area Measurement System (WAMS) for system supervision [6, 19].

TABLE I CURRENT AND FUTURE SCINARIOS OF POWER SYSTEM CONTROL (THE ROLE OF TSO)

| | Current status | Future scenario |
|---|---|---|
| *Measurement and monitoring* | • State estimation using slow, unsynchronized, and unreliable SCADA<br>• Poor and insufficient visualization<br>• Monitoring and display monologue<br>• Alarming without analyzing priorities, root causes, consequences, and counter reactions<br>• Miscellaneous communication standards | • Online state monitoring using PMU based WAMs<br>• Advanced visualization techniques based on efficient data processing by e.g. data mining<br>• Prioritized alarm processing with root cause analysis, consequence evaluation and counter-reaction planning [28]<br>• Common communication Standard |
| *Analysis* | • Offline contingency analysis<br>• Offline models for power flow and dynamic analysis<br>• Deterministic security analysis without prognosis<br>• Well established load forecast but limited forecast capability for wind and other renewables | • Model based online contingency assessment<br>• Probabilistic contingency analysis and with early warning capability<br>• Enhanced the wind and other renewables forecast capability |
| *Grid control and operation* | • Frequency and power balancing control relies on traditional resources close to be exhausted<br>• Little coordination between TSOs<br>• Protection with fixed settings | • Frequency and power balancing using new measures<br>• Enhanced coordination between TSOs<br>• Adaptive protection settings |

The recognized balancing measures of future interests include but are not limited to [6],

- Electrical energy storage technologies, e.g. Compressed-air energy storage (CAES), flywheel, and vanadium flow battery.
- Improved thermal generation technologies that has high flexibility in production
- Demand side options (details in Section F)
- Integration with other systems such as the district heating and transportation system (details in Section F)
- The enhanced interconnections will also contribute to improvement of the balancing capability in the Danish grid.

While the forecasting method for electricity load is well established, wind power forecast has be used over 10 years, but still with limited accuracy. It is estimated that an error in the wind forecast by 1 m/s can result in an error in the active power prediction in the order of few hundred megawatts [20]. As an example, experience from Horns Rev offshore wind farm in Denmark has shown periods with significant wind power variability in Fig. 6. Another example of poor wind forecast is the January 2005 Hurricane as presented in Section II. As its amount increases, accuracy of wind power forecasts is essential for improving the system balance in power systems, and several research projects have been carried out at DTU with industrial collaborations.

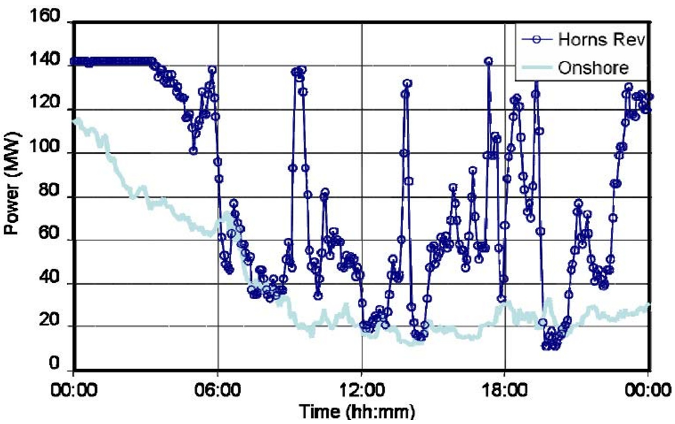



Fig. 6. Power generation of Horns Rev offshore wind farm and onshore wind turbines January 18 2005 (5 min average)

WAMS based on wide deployment of new measurement equipment such as PMUs would revolutionize the measurement and monitoring function of power system control centre. By implementing such WAMS together with new ICT technology, the current slow, unsynchronized, and less reliable state estimation would evolve into real time, synchronized, highly reliable state monitoring. Consequently, system controllability and TSO situation awareness will be largely improved. Furthermore, the WAMS will also give TSO the possibility to develop enhanced analytical capability such as online adaptive system modeling and contingency screening and analysis. Combined with geographical information system (GIS) system, the future WAMS system can further enhance the supervision of the entire network and speed up the operational and planning activities for locating and evaluating grid faults, accordingly maintenance planning.

### D. *Electricity Generation*

The current picture of the generation sector in Denmark presents a mix of centralized fossil fueled thermal plants, plus moderate amount of wind power and other small DG units that have limited controllability, and therefore incapable of system services for real and reactive supports. In contrast, the future generation sector will see a reduced number of fossil fueled units with improved thermal and electrical efficiency, and an increased number of high efficient micro CHPs and other DGs with low or no carbon emission and enhanced controllability for system services. Particularly by 2025, the 50% electricity demand in Denmark will be supplied mainly from large scale, far offshore wind farms. The wind turbines system should have large capacity and high efficiency and are under investigation by projects like SuperWind and EU UpWind project [21, 22].

### E. *The Transmission Network*

The current transmission network relies on overhead and underground HVAC technology with bottlenecks and little flow control. The overhead technology gives negative visual impacts that become of more and more public concern in Denmark. Most importantly, monitoring the physical wellbeing of the overhead HVAC e.g. the temperature and vegetation contact etc, has not been possible as evidenced in the 2003 mega-blackout in North America.

To address environmental concerns, the future Danish transmission system will prioritize HVAC underground cable in infrastructure replacements, and one research study has been established at CET, DTU. Superconducting technology is another technology to be considered for loss reduction [29]. It is also anticipated that wide use of FACTs can enable flexible flow control and alleviate bottlenecks in the network. Enhanced cross-grid interconnections will be constructed, e.g. an HVDC link between Denmark and Netherlands, currently under consideration [23]. Furthermore, large scale and far offshore wind farms will be integrated at transmission level through HVDC for large amounts and long distant power delivery.

### F. *The Distribution Network*

Significant changes are deemed to happen within the distribution network, because it is where the end users and all kinds of DGs are connected, and the integration with other energy sectors can be implemented. The current distribution network is passively supplying energy to customers, with DGs that has little active and reactive power control. There is limited integration with other energy sectors. In case of emergency, the load shedding scheme will shed a whole area of the distribution network where more and more DGs are foreseen to exist.

Incorporation of more DGs, including wind turbines and Micro CHPs will require the future distribution network to be active in managing the control of changed power flows. The

EcoGrid.dk identifies that architecture change based on innovative concepts of the Virtual Power Plant (VPP) and MicroGrids are promising for better integration of distributed resources. The former adopts an Internet-like model, with plug and play flexibility, to virtually aggregate many geographically distributed small generators into one unit and provides market and grid services [24]. The latter is actually a concept for low voltage networks with various distributed sources, capable of self management during normal conditions as well as performing automatic islanding (resynchronisation) in events of contingency (restoration) [25]. Another important concept is the subgrid with cell-structure based on agent control technology [30, 31]. The DGs such as wind turbines that used to be free running will have to enhance frequency and voltage capability that can contribute to the system security in relation to different new architectures [26].

Integration with other sectors, especially the transportation (V2G) and heating system are important in the future and considered as core elements to enable the 2025-targets. The heating system is of interest, because the heating sector consumes considerable amount of energy, and has close interactions with the electricity system due to wide use of CHPs. This is expected in the future to be supplemented with large amounts of heat pumps and direct electric heating. The heating system is appealing because of its slow thermodynamics that can counterbalance the fast dynamical changes in electric systems, though the differences in consumption patterns of the two systems must be addressed. E.g. Fig 7 shows the electricity consumption is fairly independent of seasonal variations, whereas the heat consumption is heavily dependent on seasonal variations. Furthermore, the integration can be realised in different ways including e.g. retrofitting the district heat storage systems with electric heating elements to effectively become dump loads, and improving CHP production flexibility [7].

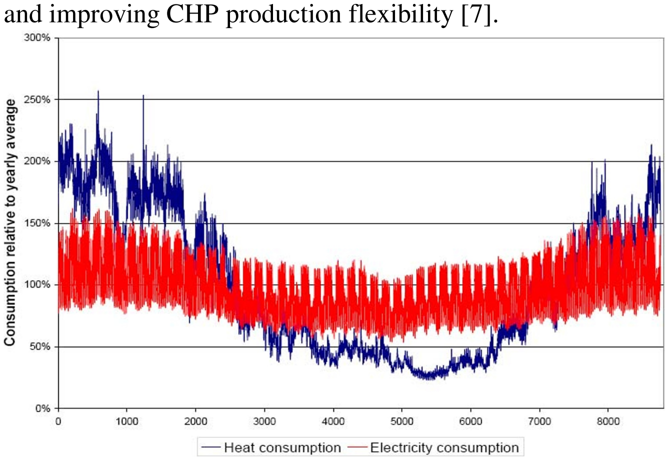



Fig. 7. Consumption patterns of electricity and district heating, 2004

The transportation is another sector of high potential for realizing 50% wind penetration. Currently CET joined forces with industrial partners (DONG Energy, IBM, Siemens etc.) in the EDISON consortium to start up a large scale research and demonstration program on integration of electric vehicles into electric power systems, which is so far the largest of its kind in the world [32].

The demand side in the future should be activated to participate into both market and system services. Potentials have been proven in the smart demand technologies, including price, frequency and voltage responsive demand technologies [18]. These new technologies will bring benefits for system security, market economy and environment, by e.g. complementing or even replacing the traditional solutions for frequency control such as the load shedding scheme in events of emergencies.

With the increased DGs, customer interruptions due to e.g. loss of upstream grid connection should no longer be excused. The intentional islanding capability for enhanced security of supply will be a prominent feature of future distribution networks that has been identified in the NextGen project, where also standardized communication systems based on IEC61850 are further developed and demonstrated for DG [27].

The current and future scenarios for generation, transmission and distribution sectors are compared and summarized in Table II, based on the EcoGird.dk and relevant projects in Denmark.

TABLE II CURRENT AND FUTURE SCINARIOS OF GENERATION, TRANSMISSION AND DISTRIBUTION SECTORS

| | Current status | Future scenario |
|---|---|---|
| *Generation* | • Fossil fueled thermal plants and some DGs with limited control and inability for system services | • Reduced fossil fueled units<br>• Increased high efficient CHP and renewable generation for CO2 reduction and enhanced controllability for system services<br>• 50% wind penetration in DK with increased large scale offshore wind farms |
| *Transmission* | • Overhead HVAC with bottlenecks and without flow control and monitoring of physical conditions e.g. temperature and vegetation contact etc.<br>• Limited interconnections between grids | • Wide use of HVAC underground cable for environmental protection and security<br>• Superconducting for loss reduction<br>• Wide use FACTs for enabling flexible flow control and alleviating bottlenecks<br>• Enhanced cross-grid interconnections<br>• HVDC connecting large scale offshore wind farm |
| *Distribution* | • Passive network for power delivery with little visibility to the TSO<br>• Some DGs without insufficient controllability<br>• Limited integration with other energy sectors<br>• Nonselective load shedding of whole area | • Active network control based on new architectures such as Cell, MicroGrids and VPP, with improved visibility to the TSO<br>• More DGs, e.g. MicroCHPs and wind turbines with enhanced frequency and voltage control<br>• Enhanced integration with other sectors, e.g. transportation (V2G) and heating system<br>• Smart and active demand in response to e.g. price, frequency and voltage<br>• Intentional islanding capability for enhanced security of supply |

## *G. Remaining Gaps*

The EcoGrid.dk program provides a long term vision for the Danish electricity network addressing the future needs. By reviewing, evaluating, and analyzing the past and current research and development activities, it sets out a research agenda with a broad portfolio of identified research needs and projects. This research portfolio is however not optimized according to priorities, and a detailed stepwise research and development plan towards 50% wind embedded electricity system has not yet been made. This is also related to the expansion planning study for future power grids, which is however not covered in the program. The planning issues to address include e.g. power reliability evaluation with high wind penetration. Particularly, crediting the wind capacity in generation planning is one critical issue to address. Examples of other issues to consider include political and legislation incentives to facilitate the implementation of EcoGrid.dk vision. It is believed the proposed EcoGrid.dk vision and research agenda will be refined and complemented as the program moves on.

## IV. Conclusion

The future power system will incorporate increased share of wind power and other renewable energy topologies, thus presenting significant challenges to many aspects of power system operation and control. To realize the new energy strategy 2025 aiming at integration of 50% wind penetration into the Danish power system, intensified research efforts are needed and for this purpose a national research program EcoGrid.dk has been initiated in Denmark. This paper synthesizes challenges facing the future power systems, and identifies and summarizes the research needs and activities in relation to the new energy strategy and the EcoGrid.dk initiative. Future work will be carried out according to the recommended research agenda in the EcoGrid.dk program, as well as the fulfillment of the remaining gaps.

## V. Acknowledgement

The paper is based on a large research program EcoGrid.dk currently undertaken at the Center for Electric Technology, Technical University of Denmark and partner contributors within the program. The program has been funded by Energinet.dk, the Danish Transmission System Operator.

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